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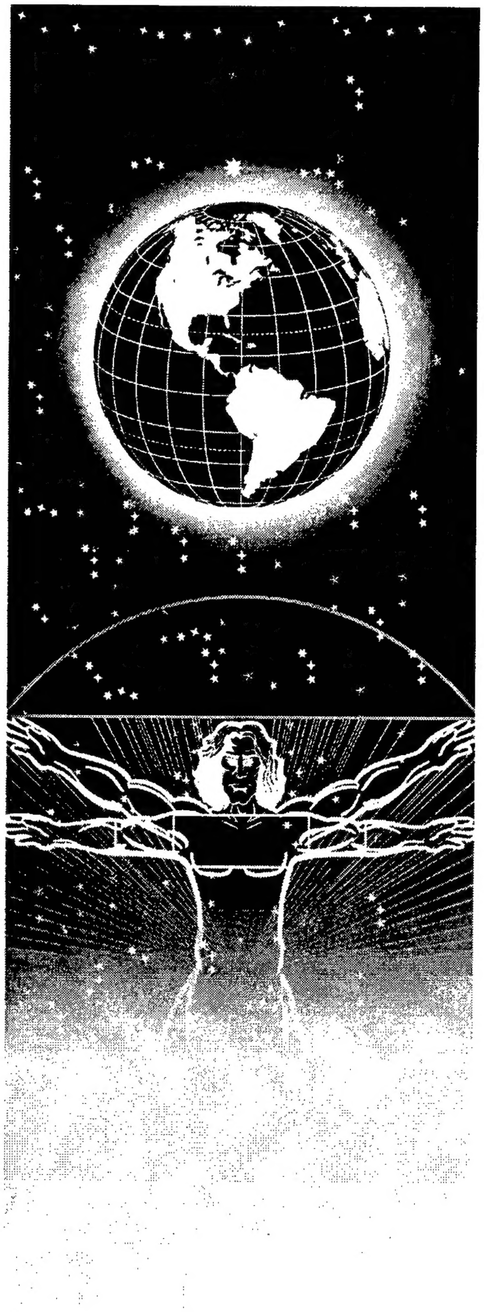

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A Taxonomy of Motion Models for Simulation and Analysis of Maintenance Tasks

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To ensure that maintenance is optimized on future weapon systems, the Air Force's Armstrong Laboratory is developing a design tools called DEPTH (Design Evaluation for Personnel, Training and Human Factors). The "virtual mockup" approach is more timely, more flexible, and less costly than a physical mockup approach. DEPTH will also be used to provide logistics support analyses and demonstrate tasks for training purposes. One of the challenges in the development of DEPTH was to provide an efficient method to control the movement of human figure models. This paper describes development of a taxonomy of motion models to allow rapid simulation and evaluation of design maintainability and human-design interaction.

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Abstract

To ensure that maintenance is optimized on future weapon systems, the Air Force's Armstrong Laboratory is developing a design tool called DEPTH (Design Evaluation for Personnel, Training and Human Factors). The "virtual mockup" approach is more timely, more flexible, and less costly than a physical mockup approach. DEPTH will also be used to provide logistics support analyses and demonstrate tasks for training purposes. One of the challenges in the development of DEPTH was to provide an efficient method to control the movement of human figure models. This paper describes development of a taxonomy of motion models to allow rapid simulation and evaluation of design maintainability and human-design interaction.

1: Introduction

All too often, weapon systems are fielded with repair problems that significantly increase long-term costs and decrease availability. The concept of design for maintainability is an attempt to ensure that these issues are addressed from early design stages. Specifically, the goals are to minimize downtime due to maintenance complexity, personnel requirements, and possibility of errors [5]. By doing this, we not only enhance operational readiness, but also reduce the maintenance burden, i.e., cost. Maintenance requirements for a weapon system's detailed design are specified through the analysis of identified maintenance tasks.

Task analysis is a four-step process [2]:

1. Allocation. This is the process of assigning maintenance tasks to the various levels of support.
2. Frequency determination. The task frequency is the probable number of times per year that a maintenance task is performed.
3. Design/description. This activity involves the development of procedures explaining how to perform the maintenance task.
4. Resource enumeration. For each maintenance task procedure developed, logistics resources such as manpower and personnel skills, tools, parts, and support and test equipment are determined.

Maintenance task analysis can identify logistics support resources both qualitatively and quantitatively by providing data for the Logistics Support Analysis (LSA) process. This task analysis is performed to find opportunities to improve designs with respect to human factors and specifically maintenance.

By adopting the general description of task components suggested by Stammers et al. [6], maintenance tasks can be viewed as consisting of three interacting aspects:

1. Definition. This is a detailed description of the maintenance task.
2. Environment. The factors in the work place that constrain or direct the actions of the maintenance personnel, either through restricting the types of activities and their sequence, or by providing aids or assistance to maintenance personnel.
3. Decomposition. This is a top-down description of the maintenance task in terms of activities to be performed by maintenance personnel within the constraints of the task environment.

Traditionally, physical mock-ups had to be built to perform task analysis and identify maintenance problems. Building such mock-ups is expensive and time-consuming. In addition, physical mockups are built too late in the acquisition process for most

redesigns since changes are much harder to accommodate. Therefore, it is the goal of the industrial and military organizations to find alternatives to physical mock-ups.

One approach is to replace physical mockups with virtual mockups originating from computer-aided design (CAD) models. In conjunction with human figure models (HFMs) it is possible to visualize human-system interaction. These virtual humans can simulate maintenance tasks on computer-based mock-ups. HFMs allow engineers to verify that maintenance is possible and visualize ways to improve the design. For example, a component may be barely out of reach, objects may obscure the visual field or impede movement, or an awkward posture may limit strength to lift a component out of a rack. HFMs allow the simulation of many different scenarios while it is still feasible to make design changes.

HFMs have been successfully used to simulate operators (i.e., drivers and pilots); however, the complexity of maintenance tasks poses additional challenges for HFM control and functionality. The challenge is to be able to control the movement of the HFMs efficiently enough for timely analysis.

This paper describes development of a taxonomy for automating the movements of HFMs through a sequence of articulation instructions that make up a human activity. Complex maintenance tasks often consist of many human motions that need to be modeled. The objective is to minimize the number of motion models used to describe a maintenance task thus reducing the time required to perform the analysis. To be effective, the motion model must be able to construct complete tasks from commands, such as "remove component."

Motion models need to do more than simply provide a script for the task. They should also support the following requirements:

- Animation.
- Rapid modeling and simulation.
- Hierarchical decomposition.
- Task time and human factors analysis.

Task time estimation is well suited for motion models. However, each model must provide a time estimation by using a fixed time or calculating a time based on its subtasks. Motion models should also provide capabilities for accessibility, visibility, and strength analysis of maintenance technicians to carry out the activity.

The taxonomy of motion models should be comprehensive enough to handle most arbitrary situations. The goal is to minimize the number of motion models used, without compromising the quality of the simulation. Given the many diverse situations that the HFM may encounter, coming up with generalized motion models is quite challenging.

2: DEPTH

The University of Iowa is developing motion models to be used by Armstrong Laboratory's (AL's) Design Evaluation for Personnel, Training and Human Factors (DEPTH) program. A simulation created by Lockheed Martin Tactical Aircraft Systems for the F-16 fighter aircraft program is shown in Figure 1. This simulation software, developed under contract to Hughes Missile Systems Company, incorporates maintenance task analysis capabilities with *Jack* -- articulated figure modeling software from the University of Pennsylvania. It also incorporates anthropometry and strength functionality developed by the University of Dayton Research Institute for AL's Crew Chief program [5].

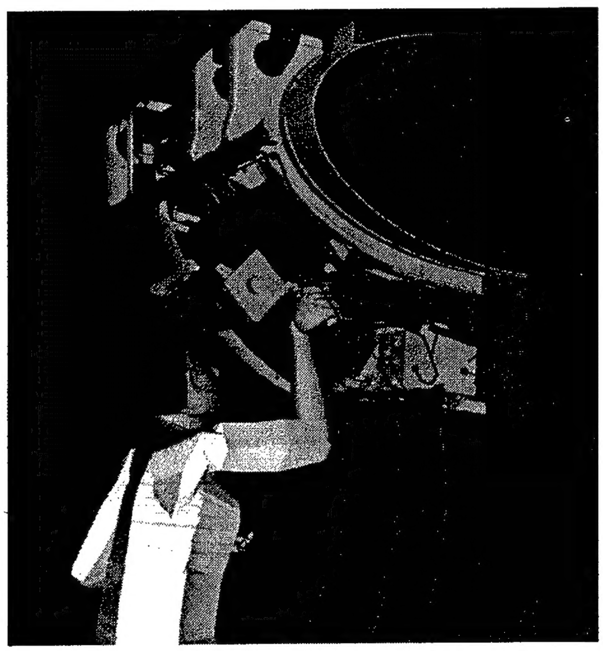

Figure 1: DEPTH Used For F-16 Analysis

By the end of this advanced development contract in late 1997, DEPTH will provide the capability to observe maintenance activities with accurate human models, clothing, tooling, fasteners, and flexible cables. In addition, it will directly feed LSA databases with information such as task times, tooling, support equipment, manpower, personnel and safety factors. Much of this information can also be used for technical manuals and maintenance training tools, so DEPTH's simulations should improve several costly acquisition processes with a single simulation.

A key to the success of DEPTH is the motion modeling capability. Without a capability to maneuver the human through environments with uncertain obstacles and aids, it is difficult to evaluate and document complete tasks. Furthermore, the decomposition capability makes it possible to treat complex tasks with a proper level of abstraction — critical both for ease of use and technical manual instructions [1]. We will now explain the basic logic of DEPTH's motion modeling capability.

3: Maintenance Task Analysis

The procedure for maintenance task analysis is outlined in Figure 2. It covers maintenance task steps 3 and 4 as described in the introductory section. For an anthropomorphic maintainability analysis, the task should be decomposed to the extent that it supports the simulation. In order to develop models of human motions to support the maintenance task analysis, it is necessary to combine required movements with the functions that are performed.

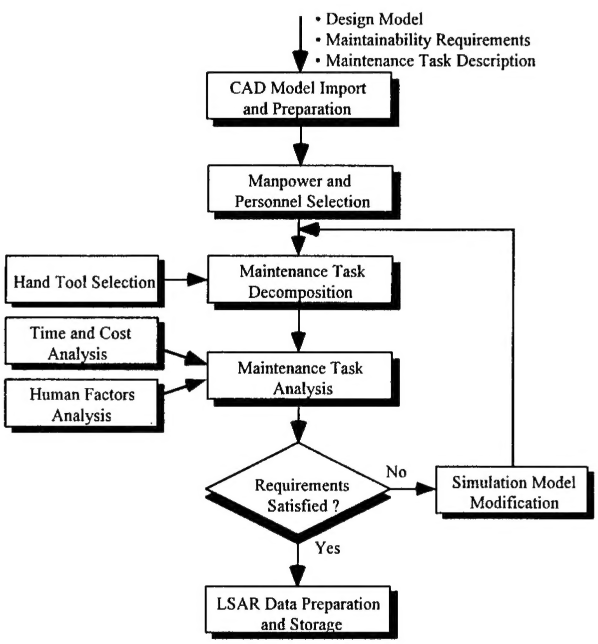

Figure 2: Maintenance Task Analysis

A framework for a hierarchical decomposition of the maintenance task into four levels is defined as follows:

1. Maintenance task level. Maintenance task typically consists of disassembly, replacement or repair of the part, and reassembly.
2. Disassembly/reassembly sequence level. The part considered is accessed by performing a sequence of disassembly steps. It is assumed that the reassembly sequence basically corresponds to the inverse of the disassembly sequence.
3. Disassembly/reassembly step level. Disassembly steps are activities aimed at the disassembly of a part or subassembly, or disconnection or disengagement of two parts.
4. Maintenance primitives level. Each disassembly step is carried out by maintenance personnel that perform required activities such as disengaging two components, performing fastening operations, various object manipulation functions, etc.

Jack human modeling software is used to define, manipulate, and animate human figures in DEPTH. However, it would be time consuming to attempt to model a complex maintenance task using basic *Jack* human motion capabilities since it could require hundreds of different basic human motions. The analysis and decomposition of the maintenance task into lowest level task descriptors allow for easier groupings. These models are grouped based on the functions to be performed, the components to be handled, and the movements needed by the human figure to perform the maintenance activity. They should be generic enough to be applied to a wide range of maintenance tasks.

4: Taxonomies of Human Behavior

The taxonomy of motion models will provide capabilities for rapid simulation, and animation of maintenance technicians performing maintenance tasks and support maintenance task analysis. Instead of defining all of the necessary human motions for each complex maintenance task individually, movements and functions can be grouped into models that can be re-used and applied to other maintenance tasks. The taxonomy of motion models will provide all the benefits of using a task taxonomy, as described in Fleishman and Quaintance [4]:

1. Task definition and analysis. Define and analyze the sequence of human motions and maintenance activities required to complete a maintenance task.
2. Time analysis. Time values can be assigned to each subtask to calculate time required to complete a task. Alternative task sequences can be evaluated in terms of completion time.
3. Cost prediction. Alternative task sequences can be evaluated in terms of cost based on completion time, tools used, and personnel involved.

4. Human-machine system design. Determine optimal task sequences based on the estimated time and cost factors related to the task.
5. Human-design interaction. Decomposition of the task enables human factors analyses (such as accessibility, visibility, and strength) at the appropriate steps.
6. Personnel selection. Determine the performance requirements of a task and coordinate them with the capabilities of the available personnel.
7. Training. By determining optimal task sequences, training requirements are identified and proper training techniques can be developed.

A taxonomic system using appropriate general descriptors can help identify and categorize human motions and maintenance activities. The resulting classifications should be a comprehensive set of models that are required to perform a wide variety of maintenance tasks.

The taxonomy of motion models to be used for the maintenance task decomposition and analysis is based on the following two approaches:

1. It follows the Behavior Description Approach to task classification, where categories of tasks are formulated based on observations and descriptions of what people actually do while performing a task [4]. This approach is based on the data collected by time and motion analysts and task analysts.
2. It is defined in a hierarchical fashion by considering behavioral processes, activities, and specific behaviors, as suggested by Berliner, et al. [2]. Quantifiable measures should be obtained for each of the specific behaviors in the scheme. The general types of measures are: (1) times — start, completion, and duration, (2) errors, (3) frequency data, (4) workload and (5) motion dynamics.

Following these two basic approaches, the tasks are classified into four categories:

1. Perceptual Tasks. The perceptual tasks in performing a maintenance task are related to identification and location of hand tools, design components, maintenance materials, and support equipment.
2. Cognitive Tasks. These tasks include information processing, problems solving, and decision making activities.
3. Communication Tasks. A maintenance technician is often required to communicate with other technicians, his supervisor, or, during debriefs, pilots.
4. Motor Tasks. Motor tasks include all maintenance activities that involve physical activities such as working with one's hands.

Tasks from all four categories should be available for analysis of the maintenance task, task time, error prediction, safety, and other human factors issues.

The scope of research reported in this paper is modeling of motor tasks, since the models of those tasks are to be integrated with DEPTH. Modeling of perceptual, cognitive, and communication tasks are currently being researched in a related Armstrong Laboratory effort.

5: A Taxonomy of Motion Models

Motor tasks represent human activities that require controlled muscular movements to perform certain maintenance activities. Since there are various levels of complexity for motor tasks, they can be represented in the following hierarchy:

1. Micro Motion. Basic human motion of a body segment such as moving arm, turning head, closing hand, etc.
2. Macro Motion. A complex human motion composed of a sequence of micro motions such as changing posture or walking.
3. Micro Model. Model of an activity that involves dealing with object manipulation or maintenance primitives by using a sequence of micro and/or macro motions.
4. Macro Model. Several micro models sequenced to accomplish complex maintenance activities.

The taxonomy of motor tasks is divided into three categories:

1. Human motions
2. Object manipulation
3. Maintenance activities

The following sections attempt to present a complete taxonomy of motor tasks in these three categories.

5.1: Human Motions

Human motions are classified into the following three sub-categories:

1. Basic motions
2. Locomotive
3. Posture change

Table 1 illustrates the basic body segment movements.

Arm Motion
Finger Motion
Torso Motion
Pelvis Motion
Open Hand Motion
Close Hand Motion
Head Motion
Eye Motion
Center of Mass Motion
Heel Motion
Foot Motion
Joint Motion

Table 1: Basic Human Motions

Motion models that represent basic human motions are not just an implementation of basic human motions available in DEPTH, but also take into account the environment surrounding the human figure being manipulated. In addition, the motion models are parameterized to be applicable for various scenarios. The walk model, for example, animates a human figure walking to the maintenance workplace while avoiding obstacles.

Most maintenance tasks require the technician to change body position several times to carry out an activity. The following capabilities should be provided to support such posture changes:

1. Basic human postures such as standing, bending, squatting, etc.
2. Simulation and animation of moving from one posture to another.
3. Adjusting a posture in such a way that the human can see a particular location, while maintaining body balance.

DEPTH supports positioning the human figure in postures shown in Table 2.

Standing
Bending
Crawling
Squatting
Climbing
Kneeling On One Knee
Kneeling On Both Knees
Lying Prone
Lying Supine
Lying Side

Table 2: Standard Human Postures

The transition from one posture to another may involve several intermediate basic postures. For example, transition from standing to lying supine requires the following sequence of postures: standing-squatting-sitting-lying supine.

Macro motions for animation of posture changing typically contain several basic human motions. For example, the motion model for changing posture from standing to squatting will require torso, pelvis, center of mass, left arm and right arm motions. Defining each of these motions individually often results in an awkward animation due to complex relationships among these motions. To avoid that problem, these are grouped in a single motion model used to move a human figure into a squatting posture from any arbitrary position in the working environment.

5.2: Object Manipulation

Object manipulation motion models represent handling of various objects encountered by maintenance personnel. Functions performed through object manipulation include operating controls (e.g., buttons and switches), removing obstructions, and opening access panels.

Table 3 summarizes the motion models for handling and manipulating objects. These models should be applicable to a variety of maintenance activities handling differences in object size and shape, and the type of manipulation required.

Grasp	Attach hand(s) to object
Release	Detach hand(s) from object
Push	Extend arms to move object away
Pull	Retract arms to move object closer
Press	Push arms down to move object down
Lift	Pull arms upward to move object up
Insert	Place a component inside another
Extract	Remove a component from inside another
Attach	Connect objects
Detach	Disconnect objects
Latch	Movement to secure an object
Unlatch	Movement to un-secure an object
Open	Open an access panel
Close	Close an access panel
Turn	Physical manipulation of an object
Hold	Keep an object grasped in hand
Carry	Hold on to an object while walking

Table 3: Object Manipulation Motion Models

5.3: Maintenance Activities

Maintenance activities are classified into two sub-categories: tool handling activities and fastening operations. Although a number of the tool handling motion models will typically be included in a fastening operation model, there are maintenance activities that involve tool handling but do not represent fastening operations. Tool manipulation models are used to represent maintenance activities involving the usage of different types of tools. Table 4 describes tool handling models and gives a brief description of their functions.

Grasp tool	Wrap hand around tool handle
Release tool	Unwrap hand from tool handle
Apply tool	Movement to perform the required operation
Disengage tool	Take tool head off fastener
Move tool	Movement of tool to and from fastener location
Position tool	Place tool in the required orientation on fastener
Adjust tool	Movement to achieve desired tool setting

Table 4: Tool Handling

Since the removal and installation of fasteners still represent some of the most common maintenance activities, generic macro models that can apply to any fastening operation are developed. Table 5 illustrates these models.

Loosen Fastener With Tool, Fingers, or Hand
Tighten Fastener With Tool, Fingers, or Hand
Remove Fastener With Tool, Fingers, or Hand
Install Fastener With Tool, Fingers, or Hand

Table 5: Maintenance Primitives

6: Motion Model Implementation

The following steps are involved in motion models implementation:

1. Definition of input parameters
2. Description of activities to be performed by motion models
3. Software implementation

Each motion model requires definition of input parameters, such as the name of technician to handle the task, name of all tools involved, name of the object to be repaired or replaced, etc.

Motion models are defined to handle various situations based on the state of working environment. For example, Figure 4 shows model of activities involved in the motion model representing a fastening operation.

Parallel Transition Networks (PaT-Nets), developed by the Center for Human Modeling and

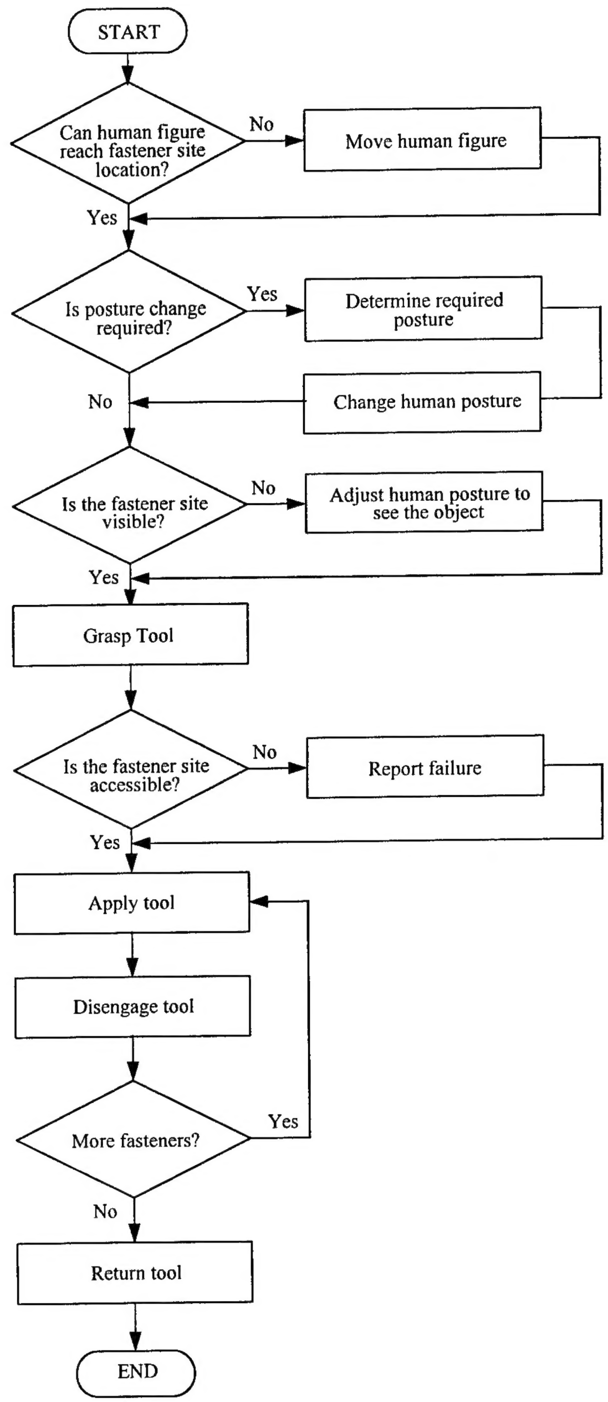

Figure 3: Loosen/Tighten Fastener With Tool

Simulation at the University of Pennsylvania, are used to implement task decomposition and the motion model taxonomy. PaT-Nets allow arbitrary activities to be scheduled including decision-making functionality. They also allow for scheduling activities performed in parallel by multiple humans.

PaT-Nets consist of a set of nodes representing different states. Each node has an associated action, and transitions between nodes. Transitions can be randomly assigned, weighted with probability, or given as a set of ordered conditions. A set of monitors adds control within the PaT-Net. This framework provides a powerful yet intuitive method for simulation control [3].

A complete task can be implemented in a hierarchy of embedded PaT-Nets corresponding to the decomposition framework described in Figure 2. The task level PaT-Net controls simulation of the overall task, including disassembly, inspection, repair, or replacement, and reassembly activities. A PaT-Net is assigned to each disassembly and reassembly step. For example, a PaT-Net will be created to simulate the disassembly step: "Detach control arm from the geared hub." Each step will typically include a sequence of motion models represented by a PaT-Net.

The time required to perform the maintenance task can be estimated based on a time database created using time data cards from the Methods Time Measurement (MTM) system. The time can be calculated for each motion model used in the simulation. The time for basic human motions can be directly retrieved from the MTM data cards. Relevant geometric information can be extracted directly from the design model displayed in DEPTH. The time for complex motion models is calculated based on basic human motions involved and the sequence of their execution.

One of the basic maintainability requirements is that the mechanical system is easy to maintain by human personnel. Human factors analysis of the task should be performed to assess feasibility and efficiency. Typically, these analyses consider requirements for strength, accessibility and visibility.

Strength analysis is used to determine feasibility of the maintenance task, i.e., ensure the maintenance technician is able to carry out an activity that requires a certain level of human strength. DEPTH provides the following two modes for strength analysis:

- *Off-line* strength analysis using Crew Chief strength algorithms to evaluate the ability of the technician to carry, lift, hold, push, and pull objects in a standard body posture. Off-line strength analysis can be performed without the animation of the maintenance task to identify design weight limits for particular human population.
- *On-line* strength analysis using dynamic strength analysis capabilities available in DEPTH that allow for calculating torque in a single joint at any arbitrary body posture. The strength window displays available torque at each degree of freedom, and the required torque necessary to carry out an activity that requires a force.

Accessibility analysis is performed to identify design problems related to the inability of maintenance personnel to access the work area.

For some disassembly activities, it is important that the technician is able to see the work area. For that purpose, DEPTH can allow the user to see approximately what the virtual technician can see.

7: Example

As an example of the hierarchical nature of motion model, let's consider the example from Figure 3. The PaT-Net that implements this fair complex motion model is depicted by the simple network in Figure 4. Notice that the details of the task can be hidden from the user allowing them to approach the task in a more natural way.

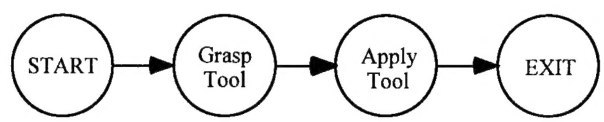

Figure 4: Top Level PaT-Net

This top level PaT-Net calls other PaT-Nets that represent additional motion models. For example, when the execution of the PaT-Net shown in Figure 4 reaches node labeled as "Grasp Tool," the action associated to this node executes a fairly complex PaT-Net, as shown in Figure 5. The "Apply Tool" PaT-Net is also executed by the action associated to the node "Apply Tool."

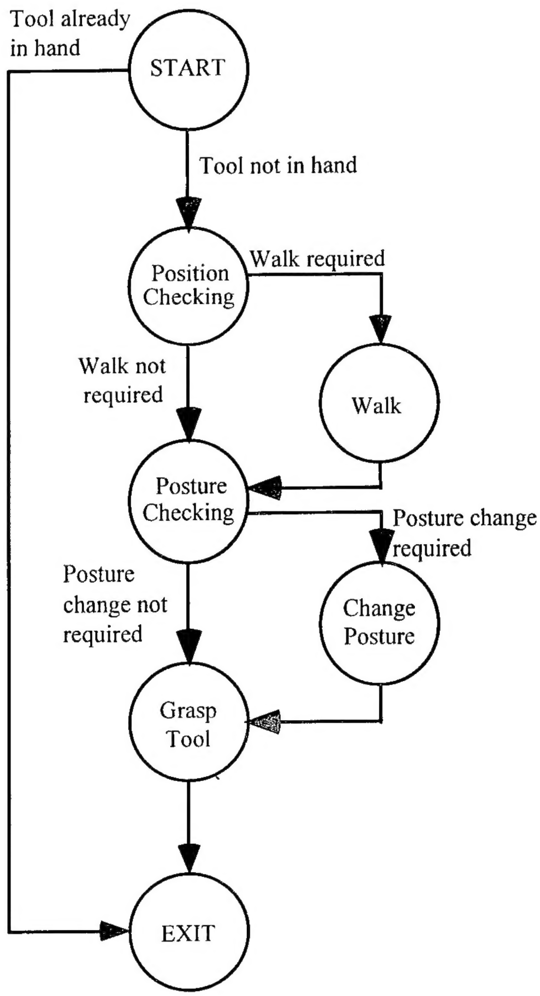

Figure 5: Grasp Tool Motion Model

8: Conclusions and Future Work

Motion modeling is a critical part of task analysis and simulation. Without a method to easily construct networks that can handle arbitrary environments, simulating human activity can be difficult at best; counterproductive at worst. We hope that the work being performed on the DEPTH contract will help make the design process more productive at a lower cost.

In the future, autonomous humans will become more powerful by making use of cognitive models such as Armstrong Laboratory's OMAR (Operator Modeling Architecture) software. OMAR models are being developed to be used in conjunction with motion models to handle unexpected obstacles or use aids in the environment.

In addition, immersive ("virtual reality") simulation will allow users to "become" the HFM. Body tracking sensors and special output devices for stereoscopic display and tactile/force feedback are making it possible for the HFM to mimic a user's movements. With continual advances in these technologies, simulated mockups will make it possible to detect problems earlier in the design process.

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